Impact of Electric Vehicles on Power Distribution Networks

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Abstract— **The market for battery powered and plug-in hybrid electric vehicles is currently limited, but this is expected to grow rapidly with the increased concern about the environment and advances in technology. Due to their high energy capacity, mass deployment of electrical vehicles will have significant impact on power networks. This impact will dictate the design of the electric vehicle interface devices and the way future power networks will be designed and controlled. This paper presents the results of an analysis of the impact of electric vehicles on existing power distribution networks. Evaluation of supply/demand matching and potential violations of statutory voltage limits, power quality and imbalance are presented.**

Keywords-component; Distribution Networks, Electic Vehicles, Distributed Generation, Smart Grids

I. Introduction

The transport sector currently relies on fossil fuels and therefore accounts for a significant part of greenhouse emissions. The passenger car is the major consumer of energy, accounting for more than half the total transportation energy [1]. Therefore, one of the main future technologies to combat greenhouse gas emissions is the battery powered Electric Vehicle (EV) and Plug-in Hybrid Electric Vehicle (PHEV). A range of passenger electric vehicles are currently being developed by different manufacturers [2]. The range of these cars is generally below 40 miles and their power ratings range from a few tens of kilowatts for small cars to a few hundred kilowatts for performance cars. Whilst at present the market for EVs is very limited, this is expected to grow with advances in new technologies, particularly in the area of high energy and power density batteries. This growth will have significant impact on the electric power supply system [3].

Electric power networks have evolved over the years to have large centrally-controlled generators connected to the high voltage side of the network and loads at the low voltage side. Consequently, power flows from the high voltage side where generators are connected to the low voltage side of the network, where medium and small size loads are connected. Increased concern over climate change and associated interest in renewable energy and energy efficiency has resulted in a continuous increase in the number of generators connected to the distribution network, typically below 33 kV. This usually relates to generators ranging in size from around 1 kW to around 5 MW and is referred to as distributed, embedded or dispersed generation [4]. Currently, distributed generation amounts to only a small proportion of the total network generating capacity, hence its impact on the network performance is negligible [5]. However, concerns have been raised about the effects of increased number of new and renewable energy resources in addition to the effects of large deployment of electric vehicles.

Recent studies [5-7] have shown that significant deployment of distributed generation creates reverse power flow in distribution networks and that bi-directional power flow can have effects on the quality of power supply and voltage levels. Distributed generation may also lead to increased fault currents, malfunction of the network protection system and phase imbalance (specific to single-phase applications).

Electric vehicles employ power electronics controllers that interface the vehicle electric power system to the grid. These controllers usually include an on-board a.c. to d.c. converter which is coupled to the grid via a single or three-phase connector. The converter can be either a diode bridge rectifier for charging the battery or a switch-mode converter which not only controls the charging of the battery, but is also capable of feeding power from the vehicle to the grid (regeneration). If properly designed and controlled, EVs can provide ancillary services and support the supply network, such as supply/demand matching and reactive power support [8]. This type of operation is part of a new concept in power systems called the 'smart grid'.

EVs may be considered as active loads, increasing the demand on the network during charging, and as generators when operating in regeneration mode. Therefore, the impact of EVs when operating in both modes, charging and regeneration, need to be analysed. The impact is expected to be significant due to the high energy capacity and mass deployment of EVs in the future. The resultant effects will dictate the design of the EV interface devices and the way future power networks will be designed and controlled.

EV interface devices may be designed to minimize or even eliminate the effects of EVs on the network fault level and protection system. However, their effects on the network loading, voltage profile, phase imbalance and power quality could be significant and need to be appropriately assessed.

The impact of the energy requirements of an increased number of electric vehicles on the UK national power grid in the short and medium terms has been evaluated by a recent study which concluded that the grid capacity should be adequate for up to 10% market penetration of EVs [9]. Whilst

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the grid capacity could be adequate, the same study stated that there could be local network problems associated with distribution network capacity and concentration of EVs.

This paper presents the results of an investigation to evaluate some of the effects of EV deployment on exisiting power distribution networks. Potential impacts of both modes of operation are analysed with emphasis on three areas: load profile and uncontrolled (increased) peak demand; change in voltage levels and violation of statutory limits; voltage imbalance (for single-phase operation).

II. SUPPLY-DEMAND PROFILES

EV interface devices may operate from a three-phase or single-phase supply points. Three-phase supply provides a larger power and hence faster charging, but availability of three-phase supply points is currently limited. However, single-phase supply is widely available and hence it is anticipated that chargers on EVs would largely be powered from a single-phase supply. Charging current is usually around 10 A for a standard charge and 30 A for a fast charge. Slow charging from a single-phase supply takes about 6 hours.

A. Network Model

A typical distribution network model, shown in the Appendix, is used for the following analysis. The network model includes the distribution network from the primary voltage level (33 kV) down to the low voltage level (400/230 V). The 33/11 kV substation has six 11 kV outgoing feeders, each supplying eight 11/0.4 kV substations. The 11/0.4 kV substation consists of four 400 V outgoing radial feeders. To simplify the analysis, only one 400 V feeder together with its connected loads and EV (if any) was modelled in detail. The other feeders together with their connected loads (and EV, if any) were represented as an individual lumped load connected to the main substation. The model assumed that each 400 V feeder supplies the equivalent of 100 individual domestic customers.

Fig. 1 shows a typical winter and summer daily load profile for domestic customers in the UK [5]. This profile is based on After Diversity Maximum Demand (ADMD) referenced to a nominal 100 consumers and measured at a distribution substation on an outgoing feeder.

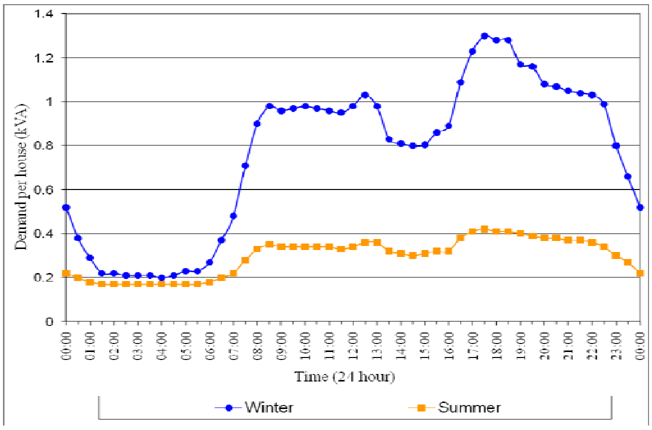

Figure 1

Typical daily load profile for a demostic load

B. Supply-Demand Matching

This section looks into scheduling of demand (charging of vehicle batteries) in order to reduce daily variations in demand, thus providing improved matching to network capacity.

As maximum demand in the UK and Europe is highest in winter, this load profile is first considered for the following analysis. Three EV penetration scenarios are considered; 10%, 20% and 30% of houses have EVs and each charge at a constant 10 A current for six hours. Three scenarios for EV charging were considered:

Scenario 1, uncontrolled domestic charging, assumes that there are no controls/incentives in place to modify load scheduling. Thus, users will tend to plug their vehicles into the charging outlets, as soon as they get home from work – at approximately 6:00 p.m. The result is that EV charging adds to the pre-existing peak load and gives an even larger peak, as shown in Fig. 2. It is noted that an increase of about 18% in maximum demand results from every 10% increase in houses with EVs. Obviously, this is the worst case scenario.

Scenario 2, off-peak domestic charging, assumes that a simple timed controller is added to the charging circuit which schedules charging to start at 1:00 a.m. and remains on until 7:00 a.m. Fig. 3 shows the improvement to the load curve and no impact on the distribution network capacity. Although the overall profile is improved, there is still a peak after midnight and a dip at around 7:00 a.m.

Scenario 3 assumes that the demand profile can be made more uniform by phasing of charging schedules. This is considered to be the 'smart' charging. Fig. 4 shows the 30 % of EV loading, split into four schedules – each 1/4 of the total charging load.

Charging scheduling required for the summer is different from that required for winter, as charging during the early morning hours would result in a peak demand at this period. Therefore, to smooth the load curve and avoid creating new peak demands, the 'smart' control system would need to be programmed or incentives created for customers to distribute charging throughout the day. A typical example of such charging is shown in Fig. 5.

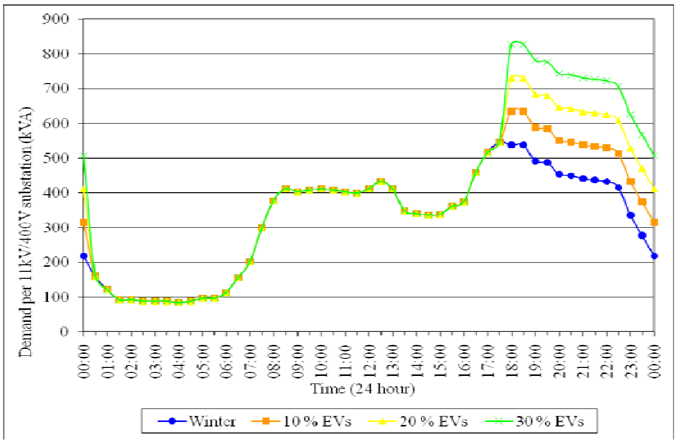

Figure 2

Winter Load Curve, EVs unscheduled

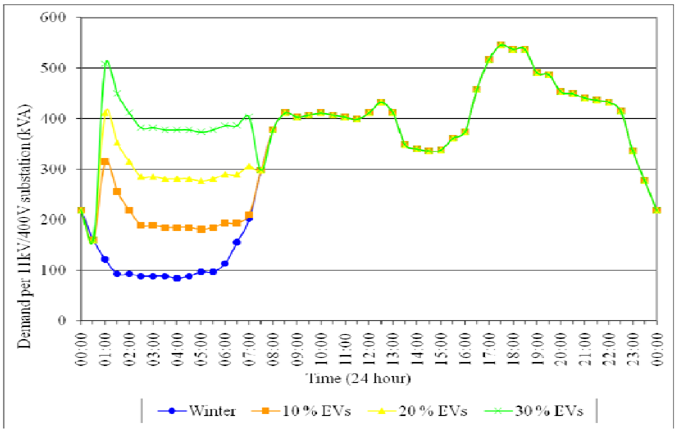

Figure 3
Winter Load Curve, EVs re-scheduled

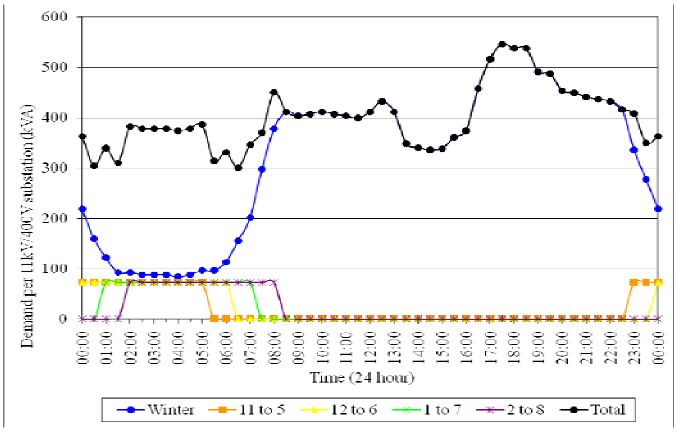

Figure 4
Winter Load Curve, EVs re-scheduled and phased

III. VOLTAGE PROFILES

Voltage levels at different substations shown on the network model given in the Appendix are analysed for minimum and maximum loading conditions with different EV penetration levels (assumed to be uniformally distributed). Two cases of EV penetration levels are assumed, these are 20% and 30% of the houses have EVs plugged to the supply.

As explained in section I, EVs may work either as a load requiring fixed charging current or as a generator feeding energy into the grid. The results presented in this section are for two extreme conditons; EVs charging at maximum loading conditions and EVs operating in regenerating mode during minimum loading conditions.

Fig. 6 shows the voltage profiles for maximum loading conditions when EVs are connected in the charging mode. As can be noted, charging of EVs has created extra loading on the feeders. At 20% level, operation of the on-load-tap-changer (OLTC) keeps the voltage levels within the statutory minmum limit of -5% (for 11 kV level) [10]. However, with 30% level, the tap changer reaches its limit and the voltages at subsations 8, 9 and 10 drop below the limit.

Fig. 7 shows the voltage profiles for minimum loading conditions and EVs opearted in the regeneration mode. As can be noted, with 20% EVs connected, the voltage at the far end is just below the maximum statutory limit of 10% (for 400 V level) [10] only with the operation of the OLTC. However, for 30% EVs level, the tap changer reaches its limit and the voltage levels at all points on the low voltage feeder exceed the statutory limit.

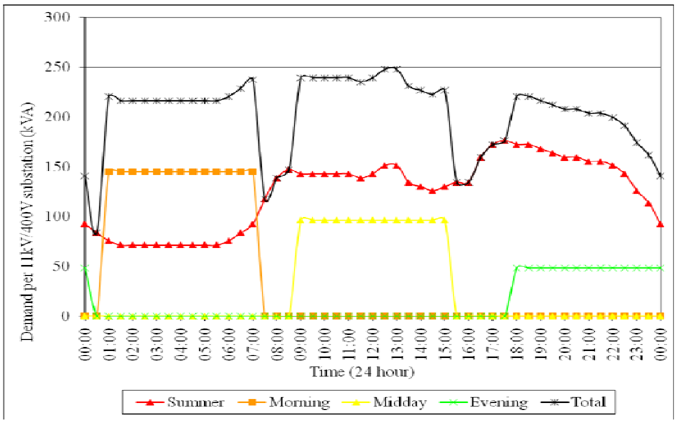

Figure 5
Summer Load Curve, EVs phased

Fig. 8 shows a similar scenario as in Fig.7, but with localized distribution of EVs (same total number on each feeder) connected to domestic customers fed from points 16 and 17 only (see Appendix). As can be seen, due to localized distribution, the voltage limit is exceeded even at 20% EVs level. This demonstrates that the extent of impact of EVs would be network specific and depends on their distribution within the network.

Fig. 9 shows the network voltage profile, assuming three EV parks at substations 7, 8 and 9 (see Appendix) each with 200 EVs and 10% EVs on all other substations. Again, two extremes are shown, one is when the EVs are charging at maximum loading condition and when EVs are regenerating at minimum loading condition. As can be noted, operation of the OLTC at the primary substation kept the voltages at all substations within limits. However, the voltage level at the far end of the feeder is near to its limit and this would be exceeded if EV penetration level increases above the 10% level (assumed in this simulation).

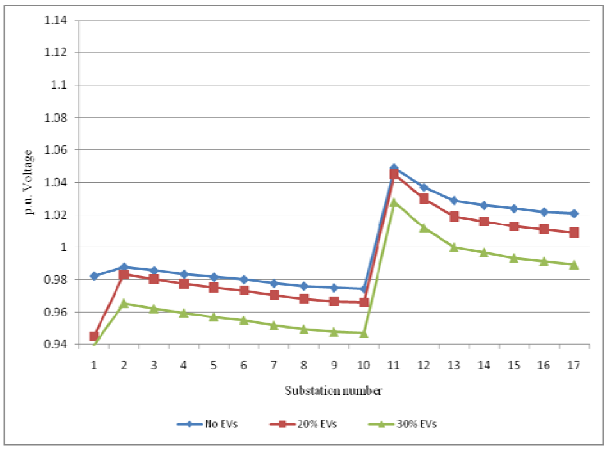

Figure 6
Voltage profiles for maximum loading and EVs in charging mode

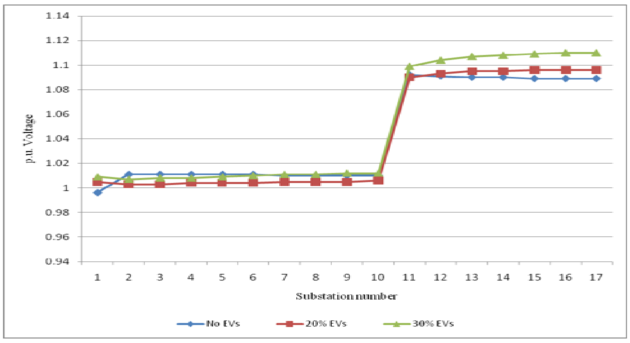

Figure 7

Voltage profiles for minimum loading and EVs in regeneration mode

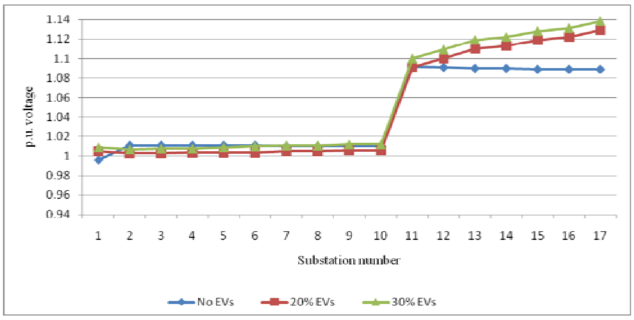

Figure 8

Voltage profiles for minimum loading and localized EVs in regeneration mode

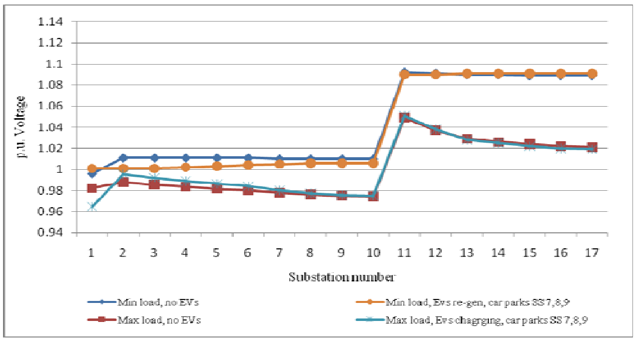

Figure 9

Voltage profiles for the network with three EV parks

IV. Statistical Analysis of Phase Imbalance

Three-phase supply provides a larger power and hence faster charging, but availability of three-phase supply points is currently limited. Single-phase powered interface devices are more practical (e.g. they allow connection to available mains supply points at homes, small buildings or special charging points in car parks). Hence the implication of this on the balance of the three-phases and consequently utilization of the system needs to be assessed.

In this analysis, an equal number of houses (connected to each phase) and an average level of EV ownership varying from 10% to 90% were assumed. This was taken as the probability that each individual house had an electric vehicle (and a charging unit). To determine the statistical variation in the EVs actually charging at any time, a large number of iterations (5000 randomly generated) were performed, with the number of charging units actually in use calculated for each iteration.

The percentage current imbalance was calculated as [11]:

$$= \frac{\text{Negative sequence current}}{\text{Positive sequence current}} \times 100 \qquad (1)$$

For every iteration, the percentage current imbalance was rounded to an integer and a count of one unit was added to the corresponding interval in the distribution.

For a given total load and source impedance, the upper limit of the percentage current imbalance that correspond to the voltage imbalance limit of 1.3 % [11] was calculated.

A range of conditions were used in the simulation including minimum and maximum domestic loading, 10%-50%-90% ownership of electric vehicles and 10%-50%-90% of charging units switched on at a given time.

In those cases with fewer chargers switched on, e.g., fewer houses in total, or with a lower percentage of EVs in use at any given time, the diversity was lower, resulting in a larger variation in the current imbalance. However, the lower total load reduced the voltage imbalance, which therefore remained within limits. Conversely, when the number of chargers switched on was high, the diversity was high, resulting in a lower average current imbalance. As a result of these two trends, the voltage imbalances remained within limits over a wide range of tested conditions.

Localized charging systems, e.g. car chargers in car parks, were also considered. In this case, the chargers are installed as part of a planned system. The model used included a car park which is supplied by a dedicated 11 kV-400/230 V, 1 MVA transformer, with no additional loads. This allowed approximately 140 units with 10 A charging current to be accommodated on each phase, or 47 units of 30 A each. For each of these cases, a set of runs was performed with different levels of EVs distributed randomly between phases.

In the case of cars charging at 10 A, the larger diversity led to a relatively small current imbalance, and only those values towards the high end of the distribution resulted in voltage imbalances, which exceeded the limit. Fig. 10 shows a histogram for the statistical distributions assuming 60% of the total car park capacity is with EVs connected randomly and plugged in for charging. The percentage current imbalance that correspond to the voltage imbalance limit of 1.3 % is shown by the vertical line at ~11%. For charging current of 30 A, the reduced diversity lead to a larger voltage imbalance.

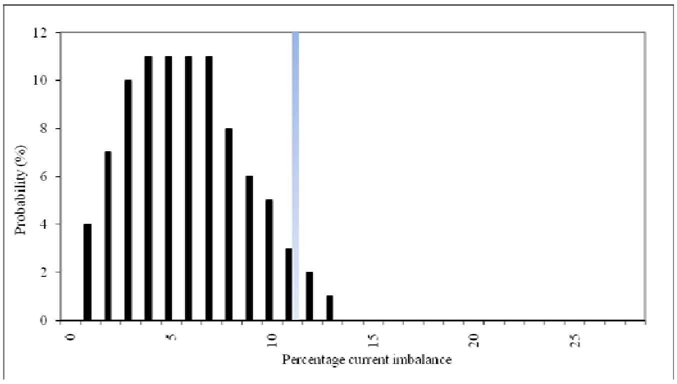

Figure 10

Histogram of statistical distributions of percentage current imbalance

V. Power Quality

EV interface devices employ power electronic converters and these are highly non-linear devices due to their operating principles and the presence of switching power semiconductor elements. Therefore, the input current of the converter generally contains high levels of harmonics and these are usually dealt with by using PWM control and filtering. Manufacturers claim that their converters produce good power quality (mainly with regard to harmonics and power factor), both in charging and regeneration modes [2]. Hence, no significant PQ issues would appear to arise during normal operation of the system, but what about PQ problems caused by a malfunction of the interface device? Fig. 11 shows the filtered EV grid current in amps and the voltage in volts for a fault condition within the converter. As can be noticed, the current is highly distorted and this could impact the local network, particularly if there are many EVs having similar problems. Note that such faults would not normally be detected by the converter overcurrent protection system.

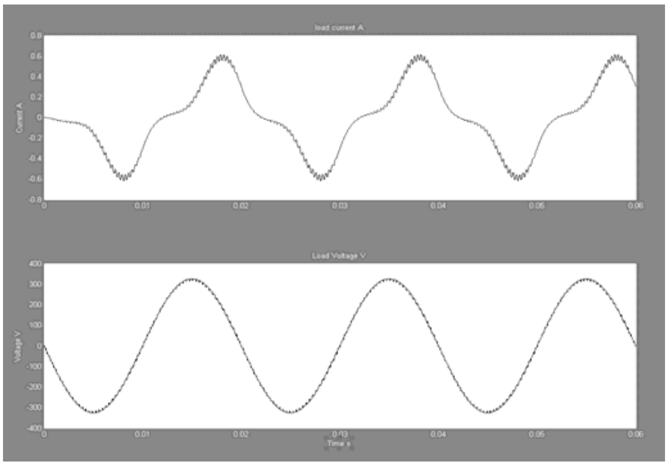

Figure 11

EV grid current and voltage for a fault condition within the converter

VI. Conclusuions

Large deployment of EVs and PHEVs is expected to lead to potential problems for existing power networks. The results of the investigation presented in this paper showed that large deployment of EVs could results in violation of supply/demand matching and statutory voltage limits. Under certain operating conditions, they may also lead to power quality problems and voltage imbalance. The latter is unlikely to exceed the statutory limit if EVs are reasonably distributed among the three phases.

EV interface devices may be designed to minimize or even eliminate the effects of EVs on the network. In fact, with appropriate control and communication with the grid, EVs could be designed to operate as part of a 'smart grid' to provide ancillary services such as supply/demand matching and voltage/frequency control.

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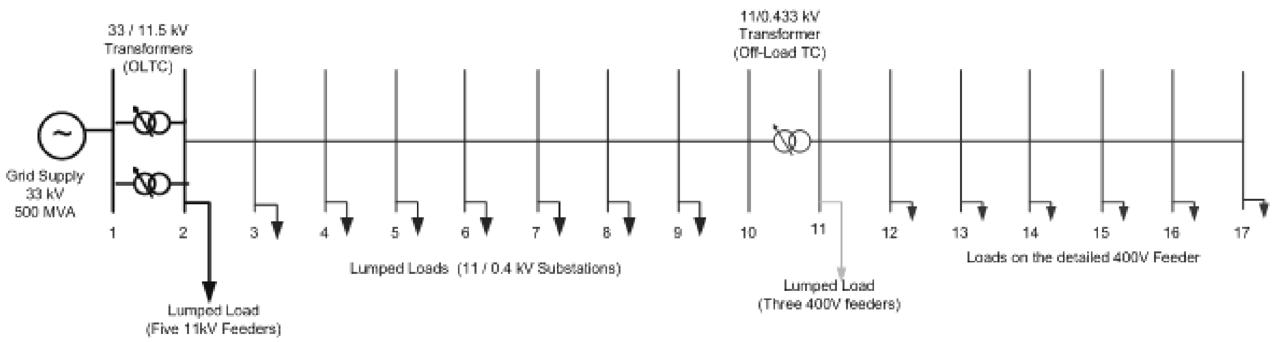
Appendix



Typical Distribution Network Model